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Implications of a 125 GeV Higgs for supersymmetric models

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Abstract

Preliminary results of the search for a Standard Model like Higgs boson at the LHC with 5 fb^{-1} data have just been presented by the ATLAS and CMS collaborations and an excess of events at a mass of $\approx$ 125 GeV has been reported. If this excess of events is confirmed by further searches with more data, it will have extremely important consequences in the context of supersymmetric extensions of the Standard Model and, in particular the minimal one, the MSSM. We show that for a standard–like Higgs boson with a mass $123 < M_h < 127$ GeV, several unconstrained or constrained (i.e. with soft supersymmetry–breaking parameters unified at the high scale) MSSM scenarios would be excluded, while the parameters of some other scenarios would be severely restricted. Examples of constrained MSSM scenarios which would be disfavoured as they predict a too light Higgs particle are the minimal anomaly and gauge mediated supersymmetry breaking models. The gravity mediated constrained MSSM would still be viable, provided the scalar top quarks are heavy and their trilinear coupling large. Significant areas of the parameter space of models with heavy supersymmetric particles, such as split or high–scale supersymmetry, could also be excluded as, in turn, they generally predict a too heavy Higgs particle.

1. Introduction

The ATLAS and CMS collaborations have released the preliminary results of their search for the Standard Model (SM) Higgs boson at the LHC on almost 5 fb^{-1} data per experiment [1]. While these results are not sufficient for the two experiments to make any conclusive statement, the reported excess of events over the SM background at a mass of $\sim$ 125 GeV offers a tantalising indication that the first sign of the Higgs particle might be emerging. A Higgs particle with a mass of $\approx$ 125 GeV would be a triumph for the SM as the high–precision electroweak data are hinting since many years to a light Higgs boson, $M_H \lesssim 160$ GeV at the 95% confidence level [2, 3]. The ATLAS and CMS results, if confirmed, would also have far reaching consequences for extensions of the SM and, in particular, for supersymmetric theories (SUSY). The latter are widely considered to be the most attractive extensions as they naturally protect the Higgs mass against large radiative corrections and stabilise the hierarchy between the electroweak and Planck scales. Furthermore, they allow for gauge coupling unification and the lightest SUSY particle (LSP) is a good dark matter candidate; see Ref. [4] for a review.

In the minimal SUSY extension, the Minimal Supersymmetric Standard Model (MSSM) [4], two Higgs doublet fields are required to break the electroweak symmetry, leading to the existence of five Higgs particles: two CP–even h and H, a CP–odd A and two charged $H^\pm$ particles [5]. Two parameters are needed to describe the Higgs sector at the tree–level: one Higgs mass, which is generally taken to be that of the pseudoscalar boson M_A, and the ratio of vacuum expectation values of the two Higgs fields, $\tan\beta$, that is expected to lie in the range $1 \lesssim \tan\beta \lesssim 60$. At high M_A values, $M_A \gg M_Z$, one is in the so–called decoupling regime in which the neutral CP–even state h is light and has almost exactly the properties of the SM Higgs particle, i.e. its couplings to fermions and gauge bosons are the same, while the other CP–even state H and the charged Higgs boson $H^\pm$ are heavy and degenerate in mass with the pseudoscalar Higgs particle, $M_H \approx M_{H^\pm} \approx M_A$. In this regime, the Higgs sector of the MSSM thus looks almost exactly as the one of the SM with its unique Higgs particle.

There is, however, one major difference between the two cases: while in the SM the Higgs mass is essentially a free parameter (and should simply be smaller than about 1 TeV), the lightest CP–even Higgs particle in the MSSM is bounded from above and, depending on the SUSY parameters that enter the radiative corrections, it is restricted to values [5, 6]

$$M_h^{\max} \approx M_Z |\cos 2\beta| + \text{radiative corrections} \lesssim 110-135 \text{ GeV} \tag{1}$$

Hence, the requirement that the h boson mass coincides with the value of the Higgs particle "observed" at the LHC, i.e. $M_h \approx 125$ GeV, would place very strong constraints on the MSSM parameters through their contributions to the radiative corrections to the Higgs sector.

In this paper, we discuss the consequences of such a value of M_h for the MSSM. We first consider the unconstrained or the phenomenological MSSM [7] in which the relevant soft SUSY–breaking parameters are allowed to vary freely (but with some restrictions such as the absence of CP and flavour violation) and, then, constrained MSSM scenarios (generically denoted by cMSSM here) such as the minimal supergravity model (mSUGRA) [8], gauge mediated (GMSB) [9] and anomaly mediated (AMSB) [10] supersymmetry breaking models. We also discuss the implications of such an M_h value for scenarios in which the supersymmetric spectrum is extremely heavy, the so–called split SUSY [11] or high–scale SUSY [12] models.

In the context of the phenomenological MSSM, we show that some scenarios which were used as benchmarks for LEP2 and Tevatron Higgs analyses and are still used at the LHC [13] are excluded if $M_h \approx 125$ GeV, while some other scenarios are severely restricted. In particular, only when the SUSY–breaking scale is very large and the mixing in the stop sector significant that one reaches this M_h value. We also show that some constrained models, such as the minimal versions of GMSB and AMSB, do not allow for a sufficiently large mass of the lighter Higgs boson and would be disfavoured if the requirement $M_h \approx 125$ GeV is imposed. This requirement sets also strong constraints on the basic parameters of the mSUGRA scenario and only small areas of the parameter space would be still allowed; this is particularly true in mSUGRA versions in which one sets restrictions on the trilinear coupling. Finally, in the case of split or high–scale SUSY models, the resulting Higgs mass is in general much larger than $M_h \approx 125$ GeV and energy scales above approximately 10^5–10^8 GeV, depending on the value of $\tan\beta$, would also be disfavoured.

2. Implications in the phenomenological MSSM

The value of the lightest CP–even Higgs boson mass $M_h^{\max}$ should in principle depend on all the soft SUSY–breaking parameters which enter the radiative corrections [6]. In an unconstrained MSSM, there is a large number of such parameters but analyses can be performed in the so–called "phenomenological MSSM" (pMSSM) [7], in which CP conservation, flavour diagonal sfermion mass and coupling matrices and universality of the first and second generations are imposed. The pMSSM involves 22 free parameters in addition to those of the SM: besides $\tan\beta$ and M_A, these are the higgsino mass parameter μ, the three gaugino mass parameters M_1, M_2 and M_3, the diagonal left– and right–handed sfermion mass parameters $m_{\tilde{f}_{L,R}}$ (5 for the third generation sfermions and 5 others for the first/second generation sfermions) and the trilinear sfermion couplings A_f (3 for the third generation and 3 others for the first/second generation sfermions). Fortunately, most of these parameters have only a marginal impact on the MSSM Higgs masses and, besides $\tan\beta$ and M_A, two of them play a major role: the SUSY breaking scale that is given in terms of the two top squark masses as $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ and the mixing parameter in the stop sector, $X_t = A_t - \mu \cot\beta$.

The maximal value of the h mass, $M_h^{\max}$ is then obtained for the following choice of parameters:

i) a decoupling regime with a heavy pseudoscalar Higgs boson, $M_A \sim \mathcal{O}(\text{TeV})$;

ii) large values of the parameter $\tan\beta$, $\tan\beta \gtrsim 10$;

iii heavy stops, i.e. large M_S and we choose $M_S = 3$ TeV as a maximal value[1];

iv) a stop trilinear coupling $X_t = \sqrt{6} M_S$, the so–called maximal mixing scenario [13].

An estimate of the upper bound can be obtained by adopting the maximal mixing scenario of Ref. [13], which is often used as a benchmark scenario in Higgs analyses. We choose however to be conservative, scaling the relevant soft SUSY–breaking parameters by a factor of three compared to Ref. [13] and using the upper limit $\tan\beta \sim 60$:

$$M_{h\,\text{bench}}^{\max} \;:\; \begin{array}{c} \tan\beta = 60\,,\ M_S = M_A = 3~\text{TeV}\,,\ A_t = A_b = \sqrt{6}\,M_S\,, \\ M_2 \simeq 2\,M_1 = |\mu| = \frac{1}{5} M_S\,,\ M_3 = 0.8\,M_S\,. \end{array} \qquad (2)$$

[1] This value for M_S would lead to an "acceptable" fine–tuning and would correspond to squark masses of about 3 TeV, which is close to the maximal value at which these particles can be detected at the 14 TeV LHC.

For the following values of the top quark pole mass, the $\overline{\rm MS}$ bottom quark mass, the electroweak gauge boson masses as well as the electromagnetic and strong coupling constants defined at the scale M_Z, including their 1σ allowed range [3],

$$m_t = 172.9 \pm 1,\ \bar{m}_b(\bar{m}_b) = 4.19 \pm 0.02,\ M_Z = 91.19 \pm 0.002,\ M_W = 80.42 \pm 0.003 \text{ [in GeV]} \\ \alpha(M_Z^2) = 1/127.916 \pm 0.015,\ \alpha_s(M_Z^2) = 0.1184 \pm 0.0014 \quad (3)$$

we use the programs `Suspect` [14] and `Softsusy` [15] which calculate the Higgs and superparticle spectrum in the MSSM including the most up–to–date information (in particular, they implement in a similar way the full one–loop and the dominant two–loop corrections in the Higgs sector; see Ref. [16]). One obtains the maximal value of the lighter Higgs boson, $M_h^{\rm max} \simeq 134$ GeV for maximal mixing. Hence, if one assumes that the particle observed at the LHC is the lightest MSSM Higgs boson h, there is a significant portion of the pMSSM parameter space which could match the observed mass of $M_h \approx 125$ GeV in this scenario. However, in this case either $\tan\beta$ or the SUSY scale M_S should be much lower than in Eq. (2).

In contrast, in the scenarios of no–mixing $A_t \approx A_b \approx 0$ and typical mixing $A_t \approx A_b \approx M_S$ (with all other parameters left as in Eq. (2) above) that are also used as benchmarks [13], one obtains much smaller $M_h^{\rm max}$ values than compared to maximal mixing, $M_h^{\rm max} \simeq 121$ GeV and $M_h^{\rm max} \simeq 125$ for, respectively, no–mixing and typical mixing. Thus, if $M_h \approx 125$ GeV, the no–mixing scenario is entirely ruled out, while only a small fraction of the typical-mixing scenario parameter space, with high $\tan\beta$ and M_S values, would survive.

The mass bounds above are not yet fully optimised and $M_h^{\rm max}$ values that are larger by a few (1 or 2) GeV can be obtained by varying in a reasonable range the SUSY parameters entering the radiative corrections and add an estimated theoretical uncertainty[2] of about 1 GeV. To obtain a more precise determination of $M_h^{\rm max}$ in the pMSSM, we have again used the programs `Softsusy` and `Suspect` to perform a flat scan of the pMSSM parameter space by allowing its 22 input parameters to vary in an uncorrelated way in the following domains:

$$1 \leq \tan\beta \leq 60\,,\ 50 \text{ GeV} \leq M_A \leq 3 \text{ TeV}\,,\ -9 \text{ TeV} \leq A_f \leq 9 \text{ TeV}\,, \\ 50 \text{ GeV} \leq m_{\tilde{f}_L}, m_{\tilde{f}_R}, M_3 \leq 3 \text{ TeV}\,,\ 50 \text{ GeV} \leq M_1, M_2, |\mu| \leq 1.5 \text{ TeV}. \quad (4)$$

We have discarded points in the parameter space that lead to a non–viable spectrum (such as charge and colour breaking minima which imposes the constraint $A_t/M_s \lesssim 3$) or to unrealistic Higgs masses (such as large $\log(m_{\tilde{g}}/m_{\tilde{t}_{1,2}})$ terms that spoil the radiative corrections to M_h [16]). We select the Higgs mass for which 99% of the scan points give a value smaller than it. The results are shown in Fig. 1 where, in the left–hand side, the obtained maximal value of the h boson mass $M_h^{\rm max}$ is displayed as a function of the ratio of parameters X_t/M_S. The resulting values are confronted to the mass range

$$123 \text{ GeV} \leq M_h \leq 127 \text{ GeV} \quad (5)$$

where the upper limit corresponds to the 95% confidence level bound reported by the CMS collaboration [1], once the parametric uncertainties from the SM inputs given in Eq. (3) and

[2]The theoretical uncertainties in the determination of M_h should be small as the three–loop corrections to M_h turn out to be rather tiny, being less than 1 GeV [17]. Note that our $M_h^{\rm max}$ values are slightly smaller than the ones obtained in Ref. [16] (despite of the higher M_S used here) because of the different top quark mass.

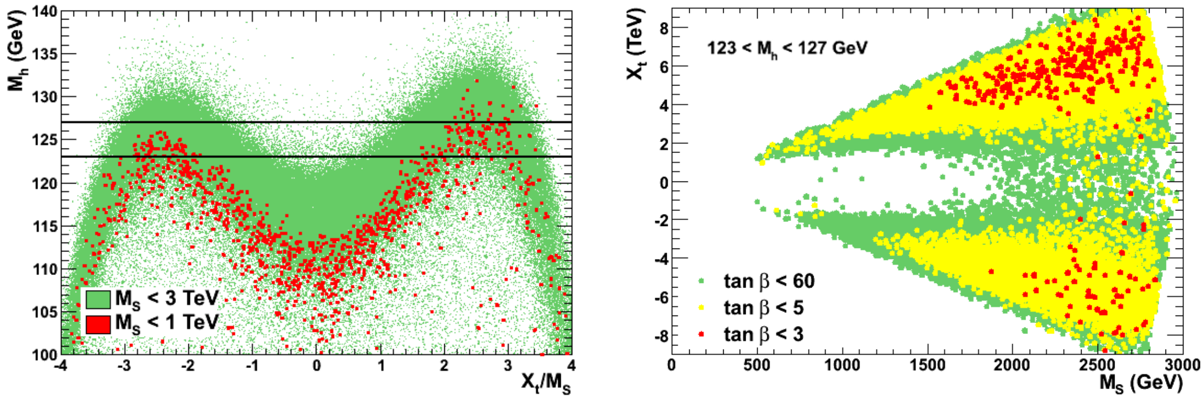

Figure 1: The maximal value of the h boson mass as a function of X_t/M_S in the pMSSM when all other soft SUSY–breaking parameters and $\tan\beta$ are scanned in the range Eq. (4) (left) and the contours for 123< M_h <127 GeV in the $[M_S, X_t]$ plane for some selected range of $\tan\beta$ values (right).

the theoretical uncertainties in the determination of M_h are included. Hence, only the scenarios with large X_t/M_S values and, in particular, those close to the maximal mixing scenario $A_t/M_S \approx \sqrt{6}$ survive. The no–mixing scenario is ruled out for $M_S \lesssim 3$ TeV, while the typical mixing scenario needs large M_S and moderate to large $\tan\beta$ values. We obtain $M_h^{\rm max}$=136, 123 and 126 GeV in, the maximal, zero and typical mixing scenarios, respectively[3].

The right–hand side of Fig. 1 shows the contours in the $[M_S, X_t]$ plane where we obtain the mass range 123 GeV $< M_h <$ 127 GeV from our pMSSM scan with $X_t/M_S \lesssim 3$; the regions in which $\tan\beta \lesssim 3, 5$ and 60 are highlighted. One sees again that a large part of the parameter space is excluded if the Higgs mass constraint is imposed[4].

3. Implications for constrained MSSM scenarios

In constrained MSSM scenarios (cMSSM)[5], the various soft SUSY–breaking parameters obey a number of universal boundary conditions at a high energy scale such as the GUT scale, thus reducing the number of basic input parameters to a handful. These inputs are evolved via the MSSM renormalisation group equations down to the low energy scale M_S where the conditions of proper electroweak symmetry breaking (EWSB) are imposed. The Higgs and superparticle

[3]We have checked that the program `FeynHiggs` [18] gives comparable values for M_h within ≈ 2 GeV which we consider to be our uncertainty as in Eq. (5).

[4]Note that the $M_h^{\rm max}$ values given above are obtained with a heavy superparticle spectrum, for which the constraints from flavour physics and sparticle searches are evaded, and in the decoupling limit in which the h production cross sections and the decay branching ratios are those of the SM Higgs boson. However, we also searched for points in the parameter space in which the boson with mass $\simeq 125$ GeV is the heavier CP–even H^0 boson which corresponds to values of M_A of order 100 GeV. Among the $\approx 10^6$ valid MSSM points of the scan, only $\approx 1.5 \times 10^{-4}$ correspond to this scenario. However, if we impose that the H^0 cross sections times branching ratios are compatible with the SM values within a factor of 2 and include the constraints from MSSM Higgs searches in the $\tau^+\tau^-$ channel, only $\approx 4 \times 10^{-5}$ of the points survive. These are all excluded once the $b \to s\gamma$ and $B_s \to \mu^+\mu^-$ constraints are imposed. A detailed study of the pMSSM Higgs sector including the dark matter and flavour constraints as well as LHC Higgs and SUSY search limits is presented in Ref. [19].

[5]In this paper cMSSM denotes all constrained MSSM scenarios, including GMSB and AMSB.

spectrum is calculated, including the important radiative corrections. Three classes of such models have been widely discussed in the literature:

– The minimal supergravity (mSUGRA) model [8], in which SUSY–breaking is assumed to occur in a hidden sector which communicates with the visible sector only via flavour-blind gravitational interactions, leading to universal soft breaking terms. Besides the scale $M_{\rm GUT}$ which is derived from the unification of the three gauge coupling constants, mSUGRA has only four free parameters plus the sign of μ: $\tan\beta$ defined at the EWSB scale and $m_0, m_{1/2}, A_0$ which are respectively, the common soft terms of all scalar masses, gaugino masses and trilinear scalar interactions, all defined at $M_{\rm GUT}$.

– The gauge mediated SUSY–breaking (GMSB) model [9] in which SUSY–breaking is communicated to the visible sector via gauge interactions. The basic parameters of the minimal model are, besides $\tan\beta$ and sign(μ), the messenger field mass scale $M_{\rm mess}$, the number of SU(5) representations of the messenger fields $N_{\rm mess}$ and the SUSY–breaking scale in the visible sector Λ. To that, one adds the mass of the LSP gravitino which does not play any role here.

– The anomaly mediated SUSY–breaking (AMSB) model [10] in which SUSY–breaking is communicated to the visible sector via a super-Weyl anomaly. In the minimal AMSB version, there are three basic parameters in addition to sign(μ): $\tan\beta$, a universal parameter m_0 that contributes to the scalar masses at the GUT scale and the gravitino mass $m_{3/2}$.

In the case of the mSUGRA scenario, we will in fact study four special cases:

– The no-scale scenario with the requirement $m_0 \approx A_0 \approx 0$ [21]. This model leads to a viable spectrum compatible with all present experimental constraints and with light staus for moderate $m_{1/2}$ and sufficiently high $\tan\beta$ values; the mass of the gravitino (the lightest SUSY particle) is a free parameter and can be adjusted to provide the right amount of dark matter.

– A model with $m_0 \approx 0$ and $A_0 \approx -\frac{1}{4} m_{1/2}$ which, approximately, corresponds to the constrained next-to–MSSM (cNMSSM) [22] in which a singlet Higgs superfield is added to the two doublet superfields of the MSSM, whose components however mostly decouple from the rest of the spectrum. In this model, the requirement of a good singlino dark matter candidate imposes $\tan\beta \gg 1$ and the only relevant free parameter is thus $m_{1/2}$ [22].

– A model with $A_0 \approx -m_0$ which corresponds to a very constrained MSSM (VCMSSM) similar to the one discussed in Ref. [20] for input values of the B_0 parameter close to zero.

– The non–universal Higgs mass model (NUHM) in which the universal soft SUSY–breaking scalar mass terms are different for the sfermions and for the two Higgs doublet fields [23]. We will work in the general case in which, besides the four mSUGRA basic continuous inputs, there are two additional parameters[6] which can be taken to be M_A and μ.

In contrast to the pMSSM, the various parameters which enter the radiative corrections to the MSSM Higgs sector are not all independent in constrained scenarios as a consequence of the relations between SUSY breaking parameters that are set at the high–energy scale and the requirement that electroweak symmetry breaking is triggered radiatively for each set of input parameters which leads to additional constraints. Hence, it is not possible to freely tune the relevant weak–scale parameters to obtain the maximal value of M_h given previously. In order to obtain a reliable determination of $M_h^{\rm max}$ in a given constrained SUSY scenario, it is

[6] This scenario corresponds to the NUHM2 discussed e.g. in Ref. [20]; the model NUHM1 also discussed in Refs. [20, 23] and which has only one additional parameter is simply a special case of our NUHM scenario.

model	AMSB	GMSB	mSUGRA	no-scale	cNMSSM	VCMSSM	NUHM
$M_h^{\rm max}$	121.0	121.5	128.0	123.0	123.5	124.5	128.5

Table 1: Maximal h^0 boson mass (in GeV) in the various constrained MSSM scenarios when scanning over all the input parameters in the ranges described in the text.

necessary to scan through the allowed range of values for all relevant SUSY parameters.

Following the analysis performed in Ref. [16], we adopt the ranges for the input parameters of the considered mSUGRA, GMSB and AMSB scenarios:

$$\begin{array}{rlll} \text{mSUGRA:} & 50~\text{GeV} \leq m_0 \leq 3~\text{TeV}, & 50~\text{GeV} \leq m_{1/2} \leq 3~\text{TeV}, & |A_0| \leq 9~\text{TeV}; \\ \text{GMSB:} & 10~\text{TeV} \leq \Lambda \leq 1000~\text{TeV}, & 1 \leq M_{\rm mess}/\Lambda \leq 10^{11}, & N_{\rm mess} = 1; \\ \text{AMSB:} & 1~\text{TeV} \leq m_{3/2} \leq 100~\text{TeV}, & 50~\text{GeV} \leq m_0 \leq 3~\text{TeV}. & \end{array}$$

Moreover, in the three cases we allow for both signs of μ, require $1 \leq \tan\beta \leq 60$ and, to avoid the need for excessive fine–tuning in the EWSB conditions, impose an additional bound on the weak–scale parameters, i.e. $M_S = M_{\rm EWSB} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} < 3$ TeV.

Using the programs `Softsusy` and `Suspect`, we have performed a full scan of the GMSB, AMSB and mSUGRA scenarios, including the four options "no-scale", "cNMSSM", "VCMSSM" and "NUHM" in the later case. Using the SM inputs of Eq. (3) and varying the basic SUSY parameters of the various models in the ranges described above, we have determined the maximal M_h value in each scenario. The results for $M_h^{\rm max}$ are shown in Fig. 2 as a function of $\tan\beta$, the input parameter that is common to all models. The highest M_h values, defined as that which have 99% of the scan points below it, for any $\tan\beta$ value, are summarised in Table 1; one needs to add ≈ 1 GeV to take into account the uncertainties in the SM inputs Eq. (3).

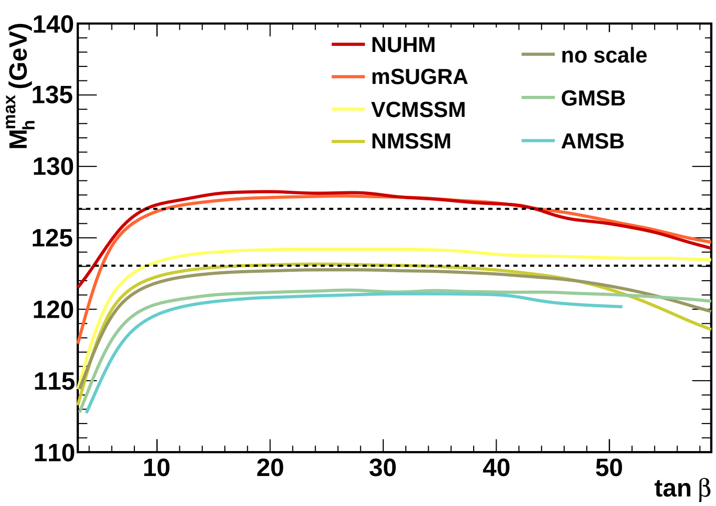

Figure 2: The maximal value of the h mass defined as the value for which 99% of the scan points have a mass smaller than it, shown as a function of $\tan\beta$ for the various constrained MSSM models.

In all cases, the maximal M_h value is obtained for $\tan\beta$ around 20. We observe that in the adopted parameter space of the models and with the central values of the SM inputs, the

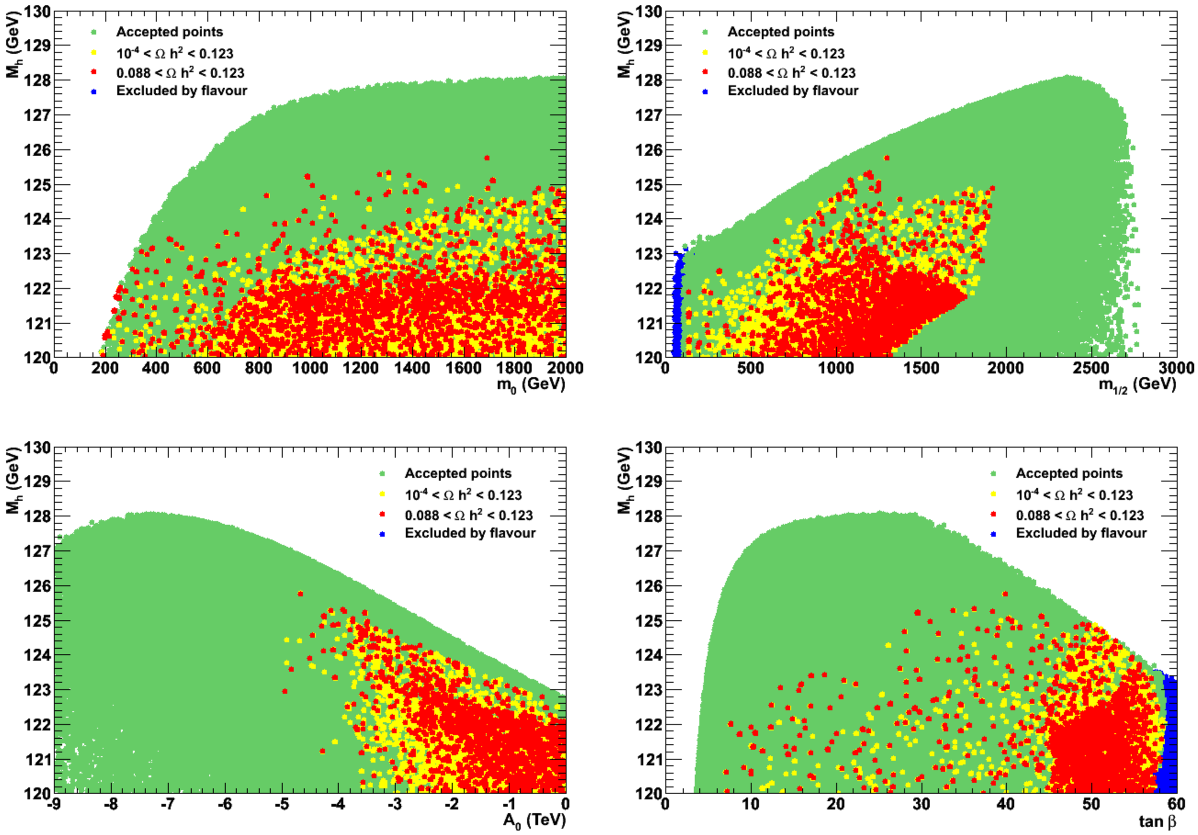

Figure 3: The value of M_h as a function of one mSUGRA continuous parameter when a scan is performed on the other parameters. The constraints from Higgs and SUSY searches at the LHC are included and the impact of flavour ($b \to s\gamma, B_s \to \mu^+\mu^-$, $B \to \tau\nu$) and DM constraints are shown.

upper h mass value (rounded to the upper half GeV) is $M_h^{\rm max} = 121$ GeV in AMSB, i.e. much less that 125 GeV, while in the GMSB scenario one has $M_h^{\rm max} = 121.5$ GeV. Thus, clearly, the two scenarios are disfavoured if the lightest CP–even Higgs particle has indeed a mass in the range $123 < M_h < 127$ GeV. In the case of mSUGRA, we obtain a maximal value $M_h^{\rm max} = 128$ GeV and, thus, some parameter space of the model would still survive the M_h constraint.

The upper bound on M_h in these scenarios can be qualitatively understood by considering in each model the allowed values of the trilinear coupling A_t, which essentially determines the stop mixing parameter X_t and thus the value of M_h for a given scale M_S. In GMSB, one has $A_t \approx 0$ at relatively low scales and its magnitude does not significantly increase in the evolution down to the scale M_S; this implies that we are almost in the no–mixing scenario which gives a low value of M_h as can be seen from Fig. 1. In AMSB, one has a non-zero A_t that is fully predicted at any renormalisation scale in terms of the Yukawa and gauge couplings; however, the ratio A_t/M_S with M_S determined from the overall SUSY breaking scale $m_{3/2}$ turns out to be rather small, implying again that we are close to the no–mixing scenario. Finally, in the mSUGRA model, since we have allowed A_t to vary in a wide range as $|A_0| \leq 9$ TeV, one can get a large A_t/M_S ratio which leads to a heavier Higgs particle. However, one cannot easily reach A_t values such that $X_t/M_S \approx \sqrt{6}$ so that we are not in the maximal–mixing scenario

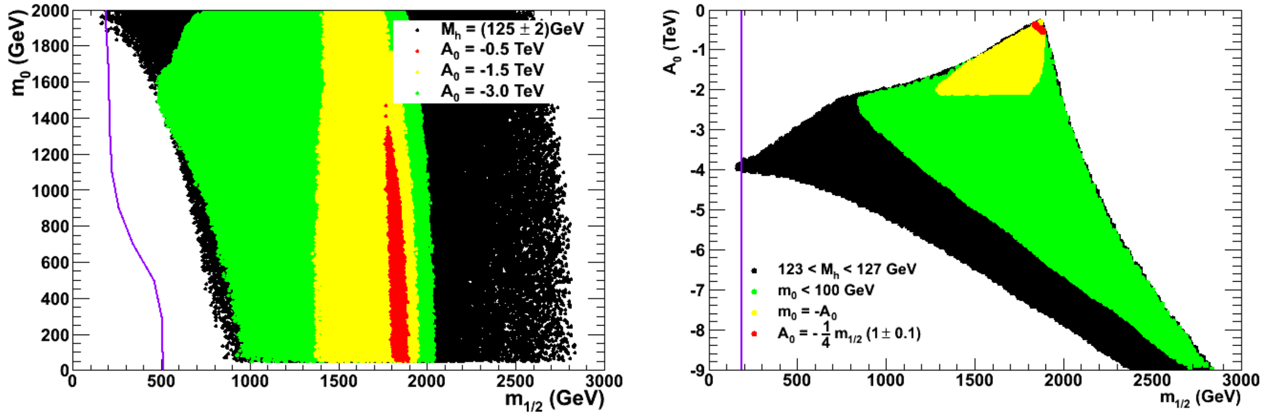

Figure 4: Contours in which $123 < M_h < 127$ GeV, resulting of a full scan of the mSUGRA parameter but for particular choices of the inputs A_0 (left) and m_0 (right). The lower bound from LHC searches of SUSY strongly interacting particles in the fully hadronic channel with 1 fb^{-1} data [24] is shown by a continuous line.

and the higher upper bound on M_h in the pMSSM is not reached.

In turn, in two particular cases of mSUGRA that we have discussed in addition, the "no–scale" and the "approximate cNMSSM" scenarios, the upper bound on M_h is much lower than in the more general mSUGRA case and, in fact, barely reaches the value $M_h \approx 123$ GeV. The main reason is that these scenarios involve small values of A_0 at the GUT scale, $A_0 \approx 0$ for no–scale and $A_0 \approx -\frac{1}{4}m_{1/2}$ for the cNMSSM. One then obtains A_t values at the weak scale that are too low to generate a significant stop mixing and, hence, one is again close to the no–mixing scenario. Thus, only a very small fraction of the parameter space of these two sub–classes of the mSUGRA model survive (in fact, those leading to the $M_h^{\rm max}$ value) if we impose $123 < M_h < 127$ GeV. These models hence should have a very heavy spectrum as a value $M_S \gtrsim 3$ TeV is required to increase $M_h^{\rm max}$. In the VCMSSM, $M_h \simeq 124.5$ GeV can be reached as $|A_0|$ can be large for large m_0, $A_0 \approx -m_0$, allowing at least for typical mixing.

Finally, since the NUHM is more general than mSUGRA as we have two more free parameters, the $[\tan\beta, M_h]$ area shown in Fig. 2 is larger than in the mSUGRA case. However, since we are in the decoupling regime and the value of M_A does not matter much (as long as it a larger than a few hundred GeV) and the key weak–scale parameters entering the determination of M_h, i.e. $\tan\beta, M_S$ and A_t are approximately the same in both models, one obtains a bound $M_h^{\rm max}$ that is only slightly higher in NUHM compared to mSUGRA. Thus, the same discussion above on the mSUGRA scenario, holds also true in the NUHM case.

In the case of the "general" mSUGRA model, we show in Figs. 3 and 4 some contours in the parameter space which highlight some of the points discussed above. Following Ref. [25] where the relevant details can be found, constraints[7] from the LHC in Higgs [19] and superparticle searches [24] and the measurement of $B_s \to \mu^+\mu^-$ as well as the requirement of a correct cosmological density as required by WMAP have been implemented. We use the program

[7]All the points in Fig. 4 correspond to the decoupling regime of the MSSM Higgs sector and, hence, to an h boson with SM cross sections and branching ratios. Furthermore, as the resulting SUSY spectrum for $M_h = 125 \pm 2$ GeV is rather heavy in constrained scenarios, one obtains very small contributions to $(g-2)_\mu$.

SuperIso Relic [26] for the calculation of dark matter relic density and flavour constraints.

4. Split and high–scale SUSY models

In the preceding discussion, we have always assumed that the SUSY–breaking scale is relatively low, $M_S \lesssim 3$ TeV, which implies that some of the supersymmetric and heavier Higgs particles could be observed at the LHC or at some other TeV collider. However, as already mentioned, this choice is mainly dictated by fine–tuning considerations which are a rather subjective matter as there is no compelling criterion to quantify the acceptable amount of tuning. One could well have a very large value of M_S which implies that, except for the lightest h boson, no other scalar particle is accessible at the LHC or at any foreseen collider.

This argument has been advocated to construct the so–called split SUSY scenario [11] in which the soft SUSY–breaking mass terms for all the scalars of the theory, except for one Higgs doublet, are extremely large, i.e. their common value M_S is such that $M_S \gg 1$ TeV (such a situation occurs e.g. in some string motivated models, see Ref. [27]). Instead, the mass parameters for the spin–$\frac{1}{2}$ particles, the gauginos and the higgsinos, are left in the vicinity of the EWSB scale, allowing for a solution to the dark matter problem and a successful gauge coupling unification, the two other SUSY virtues. The split SUSY models are much more predictive than the usual pMSSM as only a handful parameters are needed to describe the low energy theory. Besides the common value M_S of the soft SUSY-breaking sfermion and one Higgs mass parameters, the basic inputs are essentially the three gaugino masses M_1, M_2, M_3 (which can be unified to a common value at $M_{\rm GUT}$ as in mSUGRA), the higgsino parameter μ and $\tan\beta$. The trilinear couplings A_f, which are expected to have values close to the EWSB scale, and thus much smaller than M_S, will in general play a negligible role.

Concerning the Higgs sector, the main feature of split SUSY is that at the high scale M_S, the boundary condition on the quartic Higgs coupling of the theory is determined by SUSY:

$$\lambda(M_S) = \frac{1}{4}\left[g^2(M_S) + g'^2(M_S)\right] \cos^2 2\beta \ . \tag{6}$$

where g and g' are the SU(2) and U(1) gauge couplings. Here, $\tan\beta$ is not a parameter of the low-energy effective theory: it enters only the boundary condition above and cannot be interpreted as the ratio of two Higgs vacuum expectation values. In this case, it should not be assumed to be larger than unity as usual and will indeed adopt the choice $1/60 \leq \tan\beta \leq 60$.

If the scalars are very heavy, they will lead to radiative corrections in the Higgs sector that are significantly enhanced by large logarithms, $\log(M_{\rm EWSB}/M_S)$, where $M_{\rm EWSB}$ is the scale set by the gaugino and higgsino masses. In order to have reliable predictions, one has to properly decouple the heavy states from the low-energy theory and resum the large logarithmic corrections; in addition, the radiative corrections due to the gauginos and the higgsinos have to be implemented. Following the early work of Ref. [11], a comprehensive study of the split SUSY spectrum has been performed in Ref. [28]; see also Ref. [29] that appeared recently. All the features of the model have been implemented in the Fortran code SuSpect upon which the numerical analysis presented here is based.

One can adopt an even more radical attitude than in the split SUSY case and assume that the gauginos and higgsinos are also very heavy, with a mass close to the scale M_S; this is the

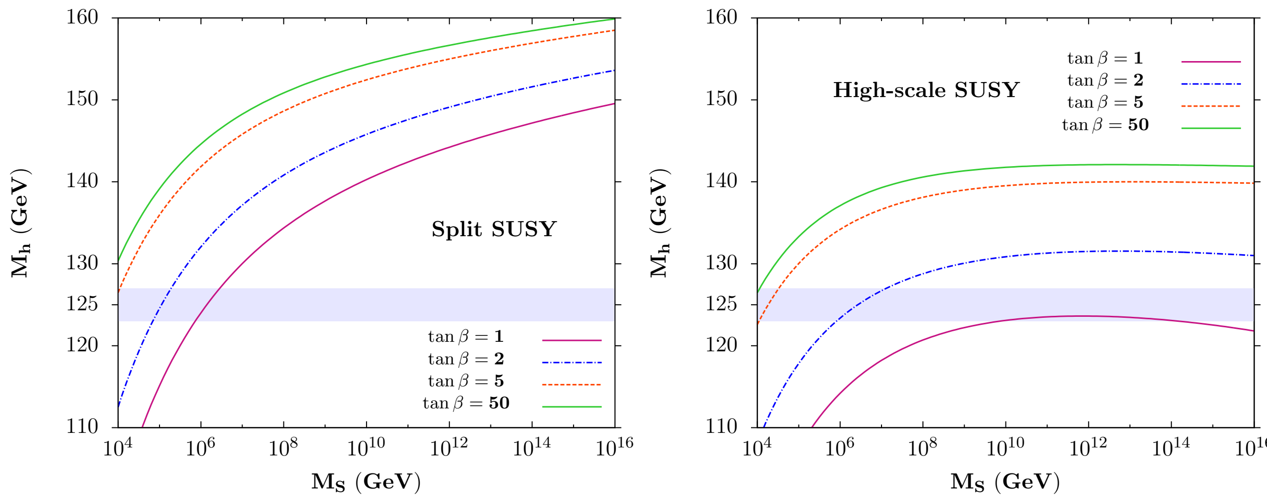

Figure 5: The value of M_h as a function of M_S for several values of $\tan\beta = 1, 2, 5, 50$ in the split SUSY (left) and high–scale SUSY (right) scenarios.

case in the so–called high–scale SUSY model [12]. Here, one abandons not only the SUSY solution to the fine-tuning problem but also the solution to the dark matter problem by means of the LSP and the successful unification of the gauge coupling constants. However, there will still be a trace of SUSY at low energy: the matching of the SUSY and the low–energy theories is indeed encoded in the Higgs quartic coupling λ given by Eq. (6). Hence, even if broken at very high scales, SUSY would still lead to a "light" Higgs boson whose mass will contain information on M_S and $\tan\beta$.

The treatment of the Higgs sector of the high–scale SUSY scenario is similar to that of split SUSY: one simply needs to decouple the gauginos and higgsinos from the low energy spectrum (in particular remove their contributions to the renormalisation group evolution of the gauge and Yukawa couplings and to the radiative corrections to the h boson mass) and set their masses to M_S. We have adapted the version of the program `Suspect` which handles the split SUSY case to also cover the case where $M_1 \approx M_2 \approx M_3 \approx |\mu| \approx M_S$. Using this program, we have performed a scan in the $[\tan\beta, M_S]$ plane to determine the value of M_h in the split SUSY and high–scale SUSY scenarios. The values given in Eq. (3) for the SM input parameters have been adopted and, in the case of split SUSY, we have chosen $M_{\rm EWSB} \approx \sqrt{|M_2\mu|} \approx 246$ GeV for the low scale. The results are shown in Fig. 5. In this figure M_h is displayed as a function of M_S for selected values of $\tan\beta$ in split and heavy–scale SUSY.

As expected, the maximal M_h values are obtained at high $\tan\beta$ and M_S values and, at the scale $M_S \approx 10^{16}$ GeV at which the couplings g and g' approximately unify in the split SUSY scenario, one obtains $M_h \approx 160$ GeV for the higher $\tan\beta = 50$ value[8]. We do not include the error bands in the SM inputs which would lead to an uncertainty of about 2 GeV on M_h, mainly due to the 1 GeV uncertainty on the top quark mass. In addition, we have assumed the zero–mixing scenario as the parameter A_t is expected to be much smaller than M_S; this approximation might not be valid for M_S values below 10 TeV and a maximal mixing

[8] Our result is different by a few GeV from that given in Ref. [29] as the gaugino/higgsino two loop RGEs were used in that reference while we include only the one–loop RGEs, and different choices for scales have been adopted. This points to sizable theoretical uncertainties that we are presently analysing.

$A_t/M_S = \sqrt{6}$ would increase the Higgs mass value by up to 10 GeV at $M_S = \mathcal{O}(1\text{ TeV})$ as was discussed earlier for the pMSSM. In the high–scale SUSY scenario, we obtain a value $M_h \approx 142$ GeV (with again an uncertainty of approximately 2 GeV from the top mass) for high $\tan\beta$ values and at the unification scale $M_S \approx 10^{14}$ GeV as in Ref. [12,29]. Much smaller M_h values, in the 120 GeV range, can be obtained for lower scales and $\tan\beta$.

Hence, the requirement that the Higgs boson mass is in the range $123 < M_h < 127$ GeV imposes strong constraints on the parameters of these two models. For this Higgs mass range, very large scales are needed for $\tan\beta \approx 1$ in the split (high–scale) SUSY scenario, while scales not too far from $M_S \approx 10^4$ GeV are required at high $\tan\beta$. Thus, even in these extreme scenarios, SUSY should manifest itself at scales much below $M_{\rm GUT}$ if $M_h \approx 125$ GeV.

5. Conclusions

We have discussed the impact of a Standard Model–like Higgs boson with a mass $M_h \approx 125$ GeV on supersymmetric theories in the context of both unconstrained and constrained MSSM scenarios. We have shown that in the phenomenological MSSM, strong restrictions can be set on the mixing in the top sector and, for instance, the no–mixing scenario is excluded unless the supersymmetry breaking scale is extremely large, $M_S \gg 1$ TeV, while the maximal mixing scenario is disfavoured for large M_S and $\tan\beta$ values.

In constrained MSSM scenarios, the impact is even stronger. Several scenarios, such as minimal AMSB and GMSB are disfavoured as they lead to a too light h particle. In the mSUGRA case, including the possibility that the Higgs mass parameters are non–universal, the allowed part of the parameter space should have large stop masses and A_0 values. In more constrained versions of this model such as the “no–scale” and approximate “cNMSSM” scenarios, only a very small portion of the parameter space is allowed by the Higgs mass bound.

Finally, significant areas of the parameter space of models with large M_S values leading to very heavy supersymmetric particles, such as split SUSY or high–scale SUSY, can also be excluded as, in turn, they tend to predict a too heavy Higgs particle with $M_h \gtrsim 125$ GeV.

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